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AIRBORNE OBSERVATIONS OF ELECTRIC FIELDS AROUND GROWING AND DECAYING CUMULUS CLOUDS

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ABSTRACT

Airborne electric-field data were gathered in an SRI International study of atmospheric electrification during the summer of 1989 near Cape Canaveral, Florida. A Learjet 36A operated by Aeromet, Inc., was instrumented with eight electric-field meters (mills) and five different particle probes. The local electric-field enhancements at each field mill site were determined under laboratory conditions and verified using in-flight data. The overdetermined system of eight equations (one for each field mill) was solved using a weighted least-squares algorithm to compute the magnitude and direction of the ambient electric field. The signal-processing system allowed the measured data to be expressed in terms of earth coordinates, regardless of the attitude of the aircraft. Thus, it was possible to take maximum advantage of the Learjet's speed and maneuverability in studying the electric-field structure in the vicinity of clouds.

Data gathered while circling just outside the boundary of a growing cumulus cloud show a nonsymmetric pattern of electric-field strength. Field intensity grew rapidly over a period of less than 10 minutes. The observed direction of the ambient electric-field vector can be explained by an ascending motion of the charge centers of a classic tripole model of a thunderstorm. A mature and decaying cumulus cloud was orbited four times. The electric-field strength again showed a nonsymmetric pattern similar to the growing cumulus. The direction of the field, however, followed a descending motion of classic tripole charge centers.

INTRODUCTION

Lightning discharge is a powerful audio and visual display of just part of the potential energy developed in convective storms. The complex nature of atmospheric electrification that can lead to the lightning discharge is related to cloud size, type, and nature of growth or decay. Understanding these relations is important to the launch community at Cape Canaveral, where the frequent thunderstorms and lightning can delay launches, can damage susceptible electronics, and pose hazards to ground personnel.

AIRBORNE PLATFORM

The platform used to gather data for this study was a Learjet 36A aircraft operated by Aeromet, Inc., of Tulsa, Oklahoma. This aircraft had been instrumented with various particle probes to measure the microphysical characteristics of clouds for previous weather reconnaisance missions over the Pacific Ocean **(Figure 1)**. Eight electric-field mills were mounted with the sensor heads flush to the skin of the aircraft at locations also shown in Figure 1. The field meter amplifier electronics and computer processing systems for all sensors were located in the main cabin of the aircraft. Data from the particle probes, forward-looking video, and other sensors were stored

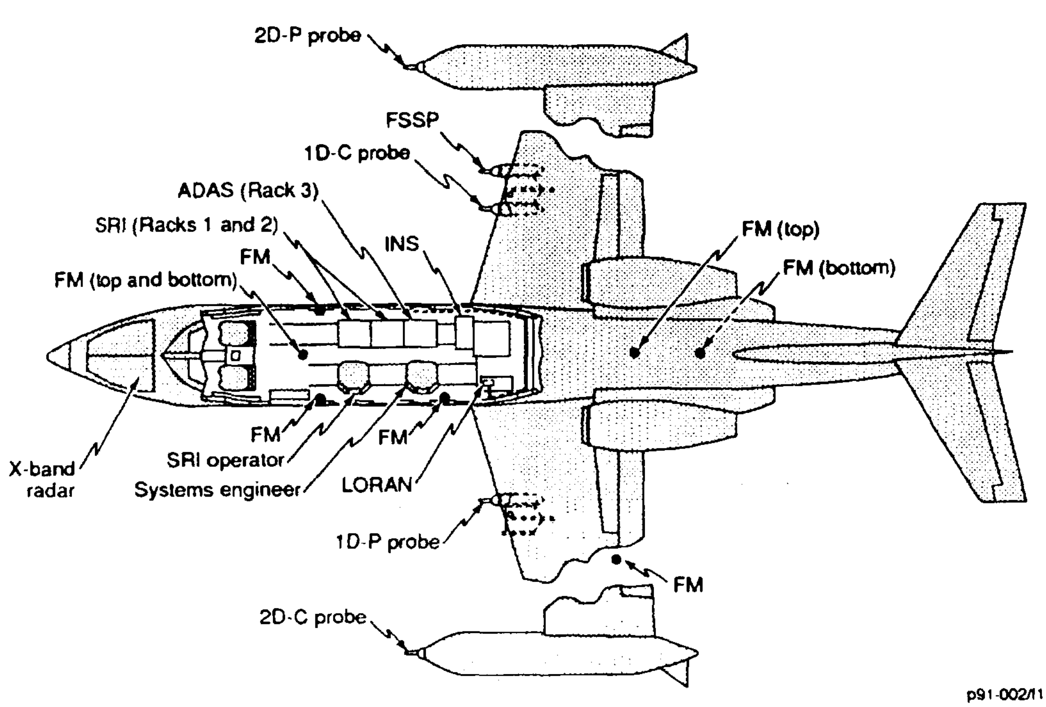

FIGURE 1. INSTRUMENTED LEARJET
The instruments include eight electric field mills (FM), five particle measuring probes (e.g., 2D-C), LORAN and INS navigation systems, and data acquisition systems (e.g., ADAS).

for comparative analysis with the stored electric-field measurements. All data could be displayed in real time, both aboard the Learjet and at a ground station.

MEASUREMENT OF ATMOSPHERIC ELECTRIC FIELD

Airborne measurements using electric-field meters of various types have been performed since the 1940s, but solving the problem of properly extracting an accurate measure of the atmospheric electric field independent of the perturbing probe has sometimes eluded researchers. The most difficult problems have been (a) to accurately determine the local electric-field perturbation due to the introduction of the airborne platform, and (b) to resolve the ambient field even in the presence of space charge about the platform. As noted by Vonnegut et al. [1], space charge around aircraft platforms can result from various mechanisms, such as (a) the electrification of aircraft exhaust, (b) triboelectric or induction charging of cloud particles that contact the aircraft during cloud penetrations, and (c) ion plumes that trail from aircraft extremities in corona. Local enhancement factors at electric-field meter sites on an airborne platform can be accurately determined using an experimental technique discussed by Kositsky and Nanevicz [2] in a companion paper. However, the three listed space charge effects, though negligible in clear air, are still a significant problem for aircraft platforms during cloud penetrations [3,4].

In the absence of space charge effects, the local electric field measured at each field mill site is a linear combination of the aircraft-perturbed ambient electric field **E** and the field resulting from nonzero aircraft potential V. The local electric fields measured at each mill site can then be expressed as

$$F_i = a_{ix}E_x + a_{iy}E_y + a_{iz}E_z + a_{iv}V \tag{1}$$

where

i = Mill number from 1 to 8

F_i = Measured electric field of Mill i

$a_{ix}, a_{iy}, a_{iz}, a_{iv}$ = Local field enhancement factors of Mill i

E_x, E_y, E_z = Vector components of the ambient electric field **E**

V = Potential of the aircraft with respect to ground.

In vector notation, the system of equations can be written $\mathbf{F} = \mathbf{AE}$. The enhancement matrix **A** contains the a_i terms, called enhancement factors, that are determined experimentally and verified using in-flight data [2]. The solution to the four unknown terms, E_x, E_y, E_z, and V, requires a minimum of four measurements, F_i. Since the described airborne system uses eight field meters, the solution to the set of eight equations is overdetermined. The additional information provided by the overdetermined system of equations can be solved using a weighted least-squares algorithm that is considerably more accurate than a system of only four equations. The general solution used for real-time computation, in matrix notation, is:

$$\mathbf{E} = \left(\mathbf{A}^T\mathbf{CA}\right)^{-1}\mathbf{A}^T\mathbf{CF} \tag{2}$$

where

A = Enhancement matrix

C = Weighting matrix

F = Field meter measurements $F_1, F_2, \ldots F_n$

E = Vector $\{E_x, E_y, E_z, V\}$.

The extra information from redundant field mills also allows for a real-time error-analysis algorithm to estimate the point-by-point uncertainty in the computed ambient electric field. Details and testing of the error-analysis and above algorithms is described in a comprehensive report by Kositsky et al. [4]. Finally, signal processing allows the atmospheric electric field to be expressed in fixed earth coordinates, regardless of aircraft orientation, as long as the orientation is known.

Case of a Rapidly Growing Cumulus

Figure 2 shows the southern region of a towering cumulus cloud taken a few minutes before the Learjet circuited just outside the cloud boundary. By flying in clear air, the measured fields are known to accurately represent the ambient electric field. The paragraphs below show that data gathered while circling a cloud with a jet aircraft can provide valuable insights into the dynamics of cloud growth and decay and can identify the internal cloud regions that have the highest electrical intensity.

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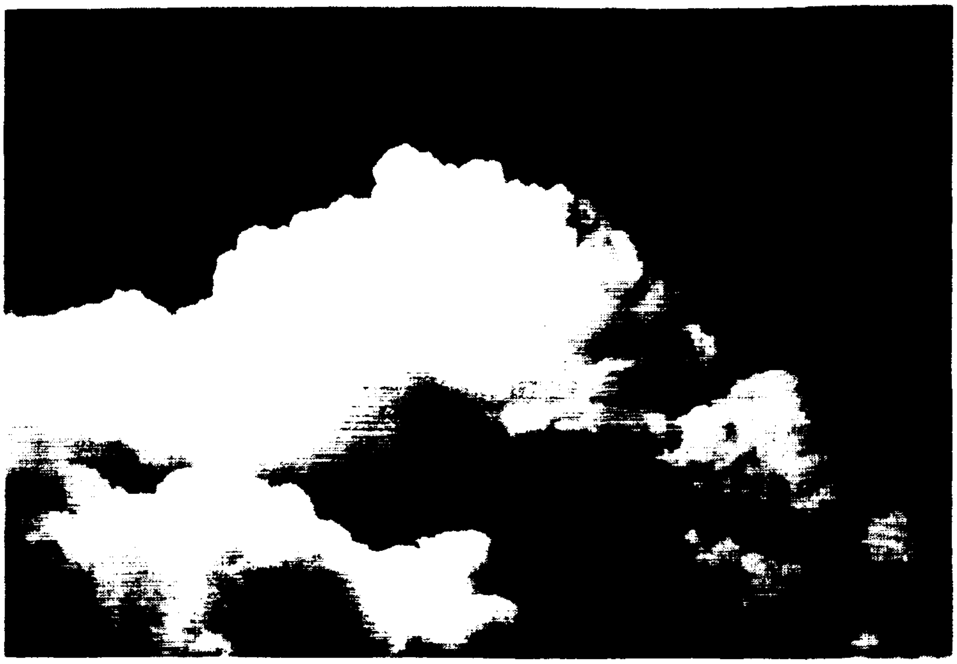

FIGURE 2. TOWERING CUMULUS
This photo was taken looking to the north at 19:10:17 UT, 1 September 1989.

The first loop around the cloud occurred at an altitude of about 5500 m. The magnitude and direction of the computed ambient electric field is plotted as a vector along the aircraft flight track in a three-dimensional perspective **(Figure 3a)**. A two-dimensional (2D) top view showing the horizontal field component of the same data set (time period) is shown in Figure 3b. The open ends of the plotted electric-field vectors are defined as the ends where an arrow would point to show the direction of motion of a positive test charge inserted into the field. The peak electric field encountered during the first pass was 0.5 kV/m along the cloud's southern boundary.

During the second pass, a peak field of 5 kV/m was measured along the southern edge (Figures 3c and 3d). The electric-field strength increased an order of magnitude between the first two passes over a time period of 3.75 minutes. During the third pass, which occurred about 5.5 minutes after the second pass, the peak field at the southern edge was 20 kV/m (Figures 3e and 3f). A summary of all three passes is shown in **Table I.**

The rapid increase in electric-field strength indicates that the cloud was indeed growing. Such growth can also be noted by following the change in the direction of the peak electric field. The direction change is interpreted to be caused by the upward motion of the charge centers in a classic tripole model of an electrified cloud. The field pattern from a generic tripole model is shown in **Figure 4.** The model consists of a large positive charge at greatest altitude, a large negative charge at some middle altitude, and a small positive charge at the lowest altitude. The three darkened vectors, labeled 1, 2, and 3, represent the peak electric-field direction vectors of the respective aircraft passes. They are mapped to the cloud model vectors

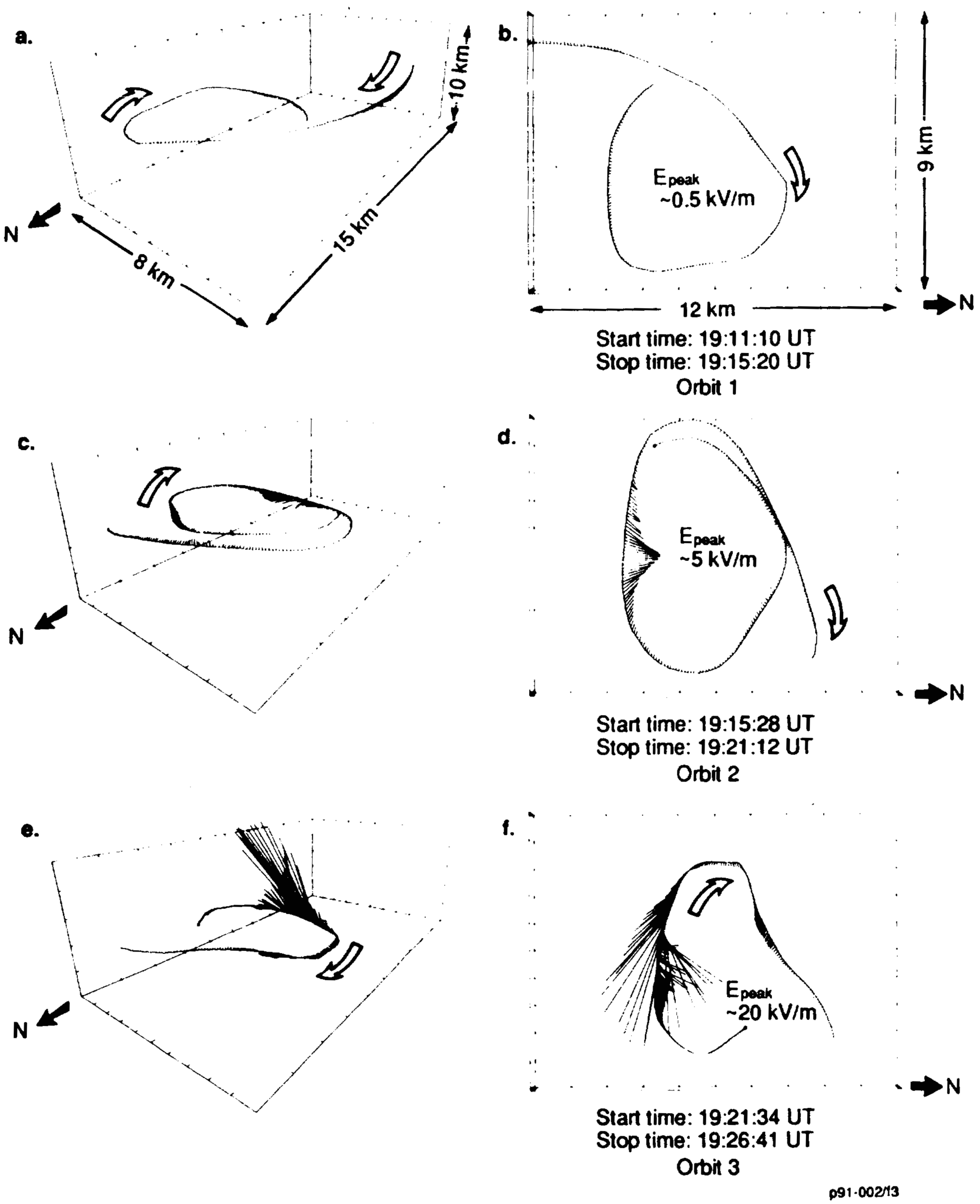

FIGURE 3. ELECTRIC-FIELD VECTOR MAPPED TO FLIGHT TRACK
These data were gathered 1 September 1989 while encircling a growing towering cumulus cloud. The peak electric field occurred on the south side of the cloud.

Table I

SUMMARY OF PEAK ELECTRIC FIELD: GROWING TOWERING CUMULUS

Orbit	Time (UT)	Flight Altitude (m)	E_{peak} (kV/m)	E_{peak} Direction
1	19:14:45	5500	0.5	N S
2	19:18:30	5200	5	
3	19:24:10	4600	20	

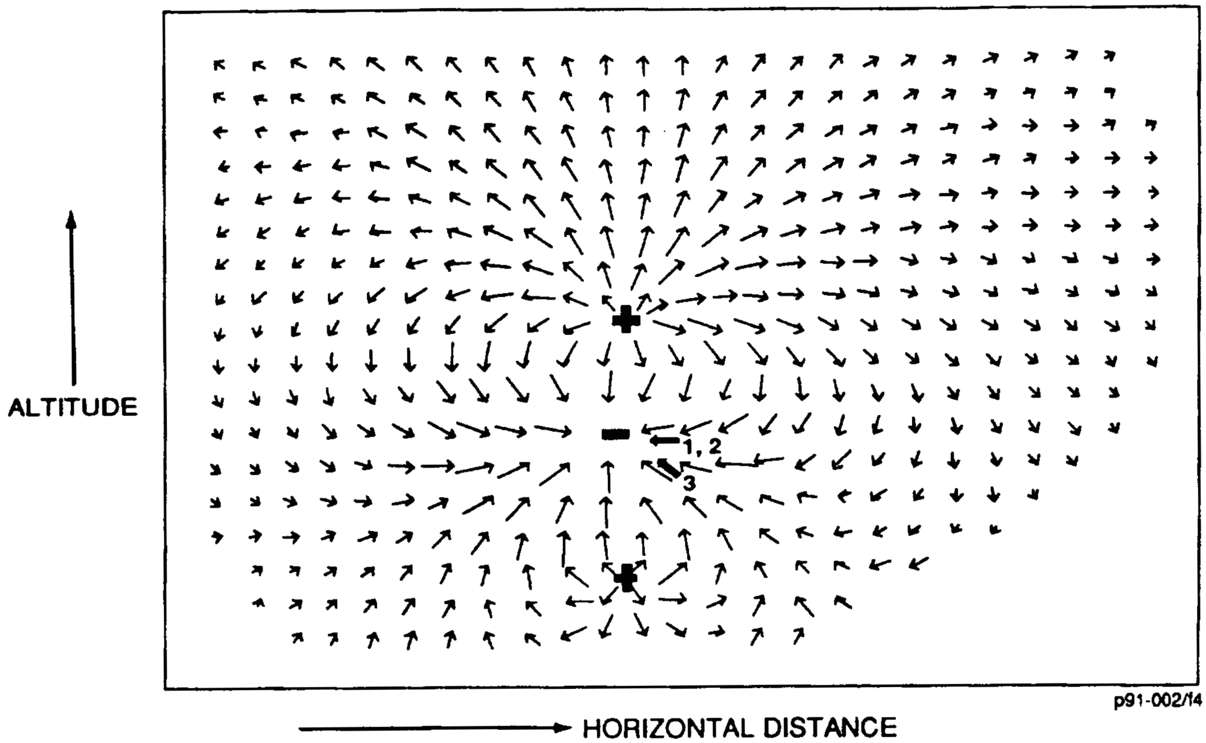

FIGURE 4. ELECTRIC-FIELD TRIPOLE CHARGE MODEL OF AN ELECTRIFIED CONVECTIVE CLOUD
Vectors 1, 2, and 3 point in the direction of the peak fields associated with the orbits shown in Figure 3. The ratio of magnitude of the charges is +20: -20: +3

according to their direction, not altitude. Although the Learjet lost some altitude while circling the cloud, which would slightly change the peak direction, the major change in the field direction is likely caused from a significant physical growth of the cloud that would carry charged particles upward and probably create many newly charged particles. For observations at constant altitude, an upward shift in the location of the top positive modeled charge would account for the increasingly upward-pointing field vector for each aircraft pass. An increase in the amount of charge at each of the modeled charge centers would account for the increasing magnitude of stored electrical potential energy.

The southern region of the cloud in Figure 3 shows vastly greater electric-field strength than the other sides. This nonsymmetry suggests that the cloud drew most of its electrical energy from the vigorous motion of air currents on one particular side of the cloud. That particular side probably caused the continuing cloud growth by drawing in a channel of moist air from below.

Case of a Mature, Decaying Cumulus

Figure 5 shows the southern region of a mature, decaying cumulus cloud. The cloud top had already exceeded 40 kft (12,000 m) before data sampling around the cloud began. The photograph suggests that the southern edge of the cloud had entrained somewhat into an anvil.

Again, the Learjet circled the cloud without penetrating it. During the first pass, performed at an altitude of 8000 m **(Figures 6a and 6b)**, the northern region of the cloud was most strongly electrified. Abrupt discontinuities in the magnitude and direction of the field typically result from nearby lightning. The peak field was 7.5 kV/m. The two-dimensional perspective shows that the small portion of the horizontal components pointing away from the cloud occurred for the peak field region, as if a larger population of positive charge were present on that side of the cloud boundary. The remaining vectors point slightly inward and down, as if there were a distribution of predominantly positive charge above and predominantly negative charge in closer proximity below.

On the second pass (Figures 6c and 6d), the peak field had increased to 11 kV/m. The direction of the peak region field was now horizontal, as if predominantly positive charge was distributed at the level of the northern boundary of the Learjet flight track.

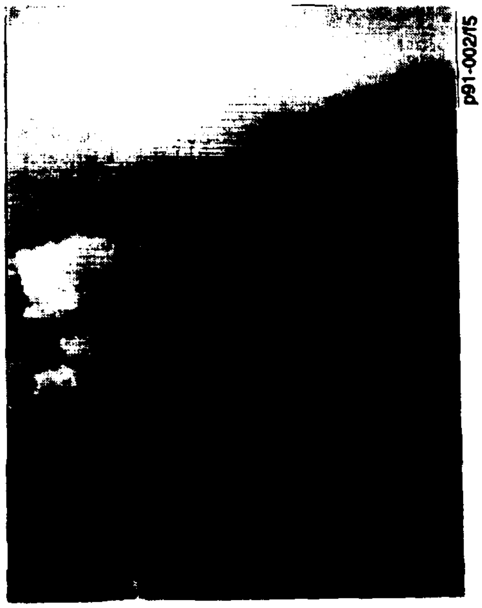

FIGURE 5. DECAYING TOWERING CUMULUS
This photo was taken looking to the north at 19:38:01 UT, 3 September 1989.

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On the third pass (Figures 6e and 6f), the ambient electric field peaked to a lesser value of 4 kV/m. The direction of the peak region field now pointed somewhat upward, as if the positive charge distribution level responsible for the horizontal peak of the second pass had now dropped below the altitude of the Learjet.

On the fourth pass (Figures 6g and 6h), the peak field had increased slightly to 6 kV/m. The peak field direction again continued its upward trend as though the positive charge distribution continued to drop.

The 2D plots (Figures 6b, 6d, 6f, and 6h) show that, on each successive pass, more and more of the field vectors pointed outward around the northern peak-field region. The horizontal component direction change is consistent with the successive upward shift of the peak field direction. That is, a downward motion of the predominant positive charge distribution occurs with the physical decay of the cloud. The negative charge distribution that would be located below the upper positive region, according to the tripole model described earlier, may also be moving downward as the cloud decays. A summary of the peak field activity is shown in **Table II.**

Table II

SUMMARY OF PEAK ELECTRIC FIELD: DECAYING CUMULUS

Orbit	Time (UT)	Flight Altitude (m)	E_{peak} (kV/m)	E_{peak} Direction
1	19:42	8000	7.5	N  S
1	19:46	8200	11	
3	19:50	8300	4.5	
4	19:54	7800	6.5	

The peak-field direction change is noted for each successive rotation about the cloud as a darkened vector, labeled 1, 2, 3, and 4 on the generic tripole cloud model of **Figure 7.** The motion of the charge centers would be downward to explain the peak field direction changes, which is opposite to the case of the growing cumulus. Since the cloud photo taken just prior to data gathering showed that the cloud was already quite mature, it is not unreasonable to propose that the cloud was decaying. Although the peak field direction change clearly indicates decay, the variation of the peak field magnitude would not have been a good indicator as it had been for the cloud growth case.

CONCLUSIONS

A Learjet 36A equipped with eight electric-field meters was used to measure the atmospheric electric field. The overdetermined system of eight equations was solved using a weighted least-squares algorithm that is considerably more accurate than a system of only four equations. The field

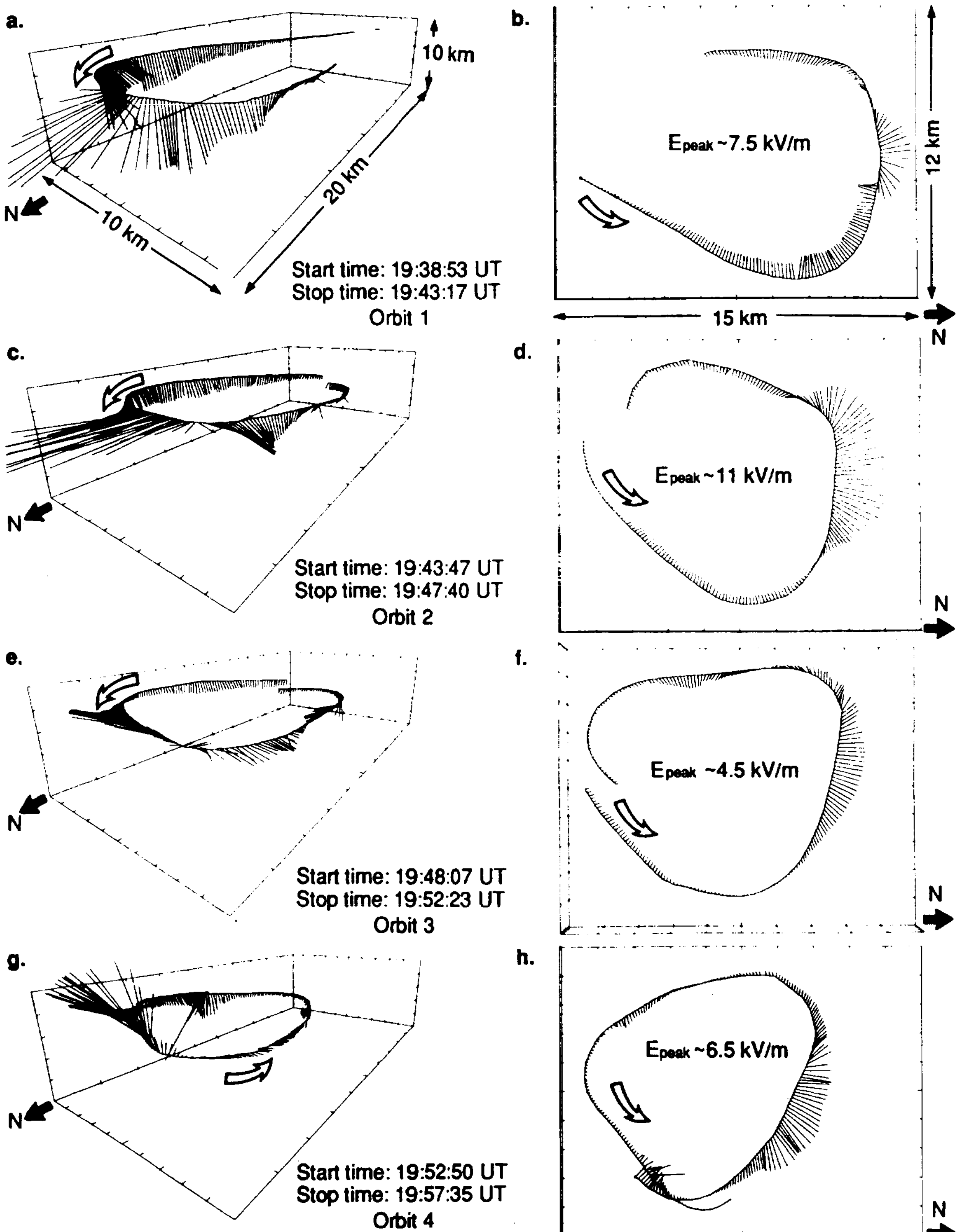

FIGURE 6. ELECTRIC-FIELD VECTOR MAPPED TO FLIGHT TRACK
These data were gathered 3 September 1989 while encircling a decaying towering cumulus cloud. The peak electric field occurred on the north side of the cloud.

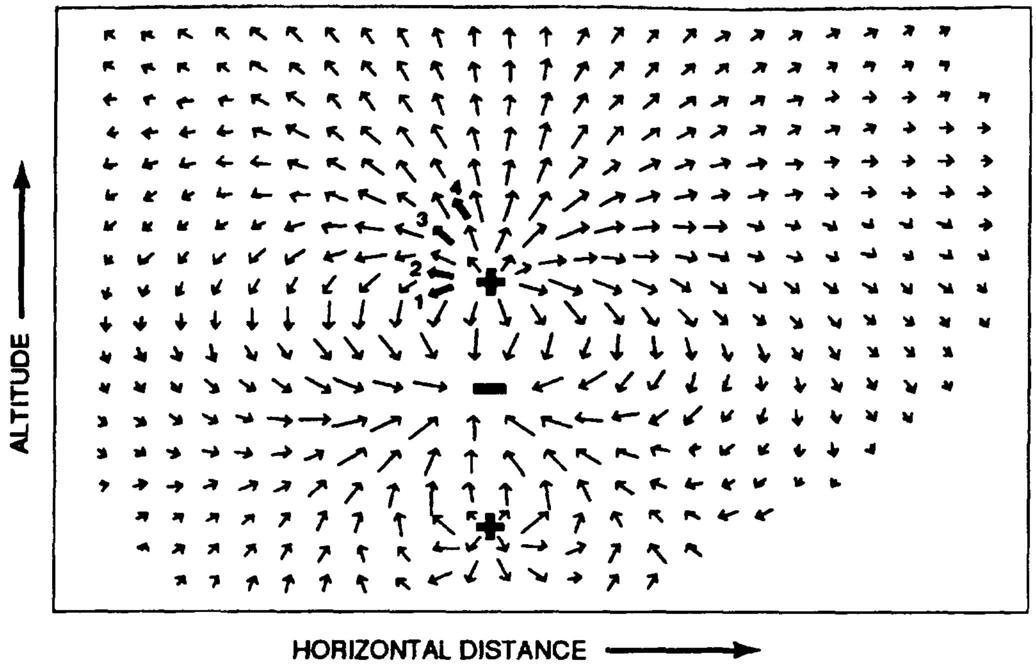

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FIGURE 7. ELECTRIC-FIELD VECTORS RESULTING FROM A TRIPOLE CHARGE MODEL Vectors 1, 2, 3, and 4 point in the direction of the peak fields associated with the orbits shown in Figure 6.

measurements were performed just outside the cloud boundary to avoid the problem of space charge effects that occur during cloud penetrations. Data gathered while circling clouds at constant altitude showed a nonsymmetric pattern of electric-field strength, which is interpreted to result from a nonsymmetric distribution of internal charge. The changing direction of the observed peak electric field was found to be a good indicator of cloud growth or decay, assuming a classic tripole model electric-field distribution. The Learjet's speed and maneuverability were effective for sampling growing and decaying cloud systems.

ACKNOWLEDGMENTS

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